ELECTROWEAK PHYSICS FROM NUTEV

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NuTeV has performed precise measurements of neutral-current to charged-current cross section ratios using intense high energy neutrino and anti-neutrino beams on a primarily steel target at the Fermilab Tevatron. A null hypothesis test of the standard model allows the extraction $\sin^2\theta_W^{\nu N}(\equiv 1 - M_W^2/M_Z^2) = 0.2277 \pm 0.0013(stat) \pm 0.0009(syst)$, a value that differs from predictions of global electroweak fits by $+3.0\sigma$.

1 Background

High energy neutrino and antineutrino beams scattered from an isoscalar target N allow measurement of two cross section ratios that can be compared to robust electroweak predictions[1] at moderate space-like momentum transfer:

$$R^{\nu}\left(R^{\bar{\nu}}\right) = \frac{\sigma\left(\nu_\mu\left(\bar{\nu}_\mu\right)N \to \nu_\mu\left(\bar{\nu}_\mu\right)X\right)}{\sigma\left(\nu_\mu\left(\bar{\nu}_\mu\right)N \to \mu^-\left(\mu^+\right)X\right)} = g_L^2 + r\left(\frac{1}{r}\right)g_R^2, \tag{1}$$

with $g_{L,R}^2 = g_{L,R}^2(u) + g_{L,R}^2(d)$, $r = \frac{\sigma\left(\bar{\nu}_\mu N \to \mu^+ X\right)}{\sigma\left(\nu_\mu N \to \mu^- X\right)} \simeq 0.5$, and, at tree level in the standard model, $g_L^2 = \frac{1}{2} - \sin^2\theta_W^{\nu N} + \frac{5}{9}\sin^4\theta_W^{\nu N}$, $g_R^2 = \frac{5}{9}\sin^4\theta_W^{\nu N}$. The combination[2]

$$R^- = \frac{R^\nu - rR^{\bar{\nu}}}{1-r} = \frac{\sigma\left(\nu_\mu N \to \nu_\mu X\right) - \sigma\left(\bar{\nu}_\mu N \to \bar{\nu}_\mu X\right)}{\sigma\left(\nu_\mu N \to \mu^- X\right) - \sigma\left(\bar{\nu}_\mu N \to \mu^+ X\right)}, \tag{2}$$

is independent of strong interaction contributions and equal, in leading order, to $R^- = \frac{1}{2} - \sin^2\theta_W^{\nu N}$.

Many experimental corrections[3] must be applied to produce the ratios in Eq. 1, and significant QCD corrections are needed to test the coupling predictions. Most notable of the latter category is the correction for charm production necessitated by the kinematic suppression associated with the charm mass. Uncertainties in the implementation of this correction limited the best experiment previous to NuTeV[4] to a precision $\Delta\sin^2\theta_W = 0.0041$, corresponding to an equivalent W mass uncertainty of 210 MeV/c^2. NuTeV constructed sign-selected neutrino beams with sufficient intensity and purity to effectively extract R^-. Corrections for charm production needed in passing from Eq. 2 to $\sin^2\theta_W^{\nu N}$ still exist, but at a considerably reduced level because they are CKM-suppressed and dependent upon only high x ($\approx$ high $\nu-$quark mass) valence quark distributions.

2 NuTeV Results and Implications

Assuming the standard model, which allows for a calculation of R^- in terms of α_{EM}, G_F, M_Z, $M_{\rm top}$, and $M_{\rm Higgs}$, NuTeV finds

$$\begin{aligned}\sin^2\theta_W^{\nu N}\left(\equiv 1 - M_W^2/M_Z^2\right) &= 0.22773 \pm 0.00135(\text{stat}) \pm 0.00093(\text{syst}) \\ &- 0.00022 \times \left(\frac{M_{\rm top}^2 - \left(175\ \text{GeV}/c^2\right)^2}{\left(50\ \text{GeV}/c^2\right)^2}\right) + 0.00032 \times \ln\left(\frac{M_{\rm Higgs}}{150\ \text{GeV}}\right),\end{aligned} \tag{3}$$

where "$\equiv 1 - M_W^2/M_Z^2$" denotes a choice of the on-shell scheme for radiative corrections[5,6] that relates $\sin^2\theta_W^{\nu N}$ directly to the physical gauge boson masses. Taking $M_{\rm top} = 175$ GeV/c^2 and

$M_{\rm Higgs} = 150$ GeV and using the precisely measured Z^0 mass, the NuTeV measurement implies $M_W = 80.14 \pm 0.08$ GeV$/c^2$. The overall $\Delta \sin^2 \theta_W^{\nu N}$ betters the previous neutrino world average by a factor of two and is statistics-dominated. The uncertainty in M_W compares favorably to that obtained from direct extractions and other precision electroweak measurements.

NuTeV also relaxes standard model assumptions and obtains the couplings[a] $g_L^2 = 0.30005 \pm 0.00137$, $g_R^2 = 0.03076 \pm 0.00110$ by omitting electroweak corrections save for the large and experiment-dependent QED parts that approximately factor. Results for $g_{L,R}^2$ have stronger dependences on the neutrino charm production model and are more likely to be affected by higher order QCD corrections than that for $\sin^2 \theta_W$[7].

2.1 Experimental Details

A description of NuTeV analysis details is available elsewhere[3].

The largest experimental uncertainty, besides statistics, is associated with imperfect knowledge of the $\sim 1.7\%$ level $\nu_e/\bar{\nu}_e$ background flux $\left(\Delta \sin^2 \theta_W^{\nu N} = 0.00039\right)$. The NuTeV beamline suppresses relatively poorly constrained neutral hadron sources of this flux, leaving charged kaon decays as the dominant source. This contribution is in turn tightly constrained by the observed $\nu_\mu/\bar{\nu}_\mu$ flux produced by $K^\pm$ in charged current event samples. Charm particle decays in the neutrino production target produce the next largest $\nu_e/\bar{\nu}_e$ flux contribution; this source is constrained by measurement of “wrong sign” charged current event rates in the experiment[8].

The largest model uncertainty in the $\sin^2 \theta_W^{\nu N}$ extraction arises from residual charged current charm production, $\left(\Delta \sin^2 \theta_W^{\nu N} = 0.00047\right)$. The magnitude of this term has been verified by others[7]. Its computed size is independent of the details of the charm production model for the $\sin^2 \theta_W^{\nu N}$ extraction from R^-.

2.2 Comparison to Other Electroweak Measurements

A global fit to all electroweak data except neutrino measurements[9] implies $\sin^2 \theta_W = 0.2227$, $g_L^2 = 0.3042$, and $g_R^2 = 0.0301$, with negligible errors compared to the NuTeV measurements. The average of direct $W-$mass measurements is $M_W = 80.45 \pm 0.04$ GeV$/c^2$. The NuTeV result is three standard deviations higher(lower) than predictions for $\sin^2 \theta_W(M_W)$, while g_L (g_R) are shifted down(up) compared to predictions. As a consequence, R^ν, $R^{\bar{\nu}}$, and R^- are all lower than predicted. The global electroweak fit without the NuTeV measurement has $\chi^2/N = 19.6/14$ (14% probability); with the NuTeV result this becomes $\chi^2/N = 28.8/15$ (1.7% probability). Essentially all of the χ^2 contribution that is greater than N comes from NuTeV and $A_{fb}^{0,b}$, the forward-backward asymmetry for $b-$quarks measured at the Z^0 pole; these are the only two measurements that prefer a large Higgs boson mass in the global fit. Without $A_{fb}^{0,b}$ and $\sin^2 \theta_W^{\nu N}$, the global fit prediction for $M_{\rm Higgs}$ would sink to ˜55 GeV$/c^2$, uncomfortably below the direct search exclusion limit– though NuTeV’s sensitivity for $M_{\rm Higgs}$ is minimal(Eq. 3) and $A_{fb}^{0,b}$ drives the fit.

The statistical situation is, in short, intriguing, but inconclusive. It lies within the bounds of reason to regard the $\sin^2 \theta_W^{\nu N}$ and $A_{fb}^{0,b}$ measurements as simple fluctuations, and to see the overall global electroweak fit result as yet another ringing endorsement of the standard model.

2.3 Possible Standard Model Explanations

Assuming the NuTeV measurement is not a fluctuation, one can consider pursue “explanations” for the “discrepancy”. Plausible standard model effects that NuTeV did not explicitely ac-

[a] These numbers have been updated to correct a small numerical error in the NuTeV publication.

count for in its analysis include nuclear shadowing, asymmetries in the nucleon strange sea, and nucleon-level isospin violation.

Shadowing can be understood as a very low Q^2 phenomenon wherein the exchanged $W^\pm$ and Z^0 bosons fluctuate into vector or axial vector mesons. Miller and Thomas[10] argue that shadowing is weaker for Z^0 exchange than for W exchange, and that $R^{\nu/\bar{\nu}}$ should therefor be increased in an iron target compared to simple partonic expectations, at least for the part of the NuTeV data sample with low Q^2. The major problem with their observation is that it has the wrong sign: NuTeV data show *smaller than expected* $R^{\nu/\bar{\nu}}$. One would also expect minimal shadowing effects in $\sin^2\theta_W^{\nu N}$ extracted from R^- because the vector-meson cross sections are charge symmetric and cancellations will thus occur in the numerator and denominator of Eq. 2.

An asymmetric strange sea ($\bar{s} \neq s$) can affect predictions for R^- since terms proportional to $s-\bar{s}$ appear in the numerator and denominator of Eq. 2. The best handle on this physics comes from a NuTeV analysis[11] of the dimuon processes $\nu_\mu/\bar{\nu}_\mu N \to \mu^\pm\mu^\mp X$. Dimuon final states are dominated by charm production, important contributions to which occur through the charged current sub-processes $\nu_\mu s \to \mu^- c$ and $\bar{\nu}_\mu \bar{s} \to \mu^+ \bar{c}$. NuTeV's separated beams permit reliable independent extractions of s and $\bar{s}$. The two distributions are found to be consistent with being equal to one another, and thus no asymmetry is observed. Taking the data at face value and analyzing it using the same cross section model used to extract $\sin^2\theta_W^{\nu N}$[12], it is again found that the sign of the (statistically weak) effect observed using the dimuon samples is *opposite* that needed to account for the weak mixing angle discrepancy. NuTeV has published its data in a nearly model-independent form that should allow more detailed examination of these ideas.

Finally, failure to take into account isospin violation can upset the mixture of u and d quark couplings used in determining $\sin^2\theta_W^{\nu N}$. NuTeV's iron target has a ˜5.7% excess of neutrons over protons. This gross effect is accounted for; in fact, computing the corresponding correction requires NuTeV to make its only significant use of parton distribution functions not extracted self-consistently from the experiment itself. The more subtle effect not explicitly corrected for occurs at the nucleon level in the possible breaking of the generally assumed identities $u_p = d_n$ and $d_p = u_n$. An early bag model calculation estimated effects on $\sin^2\theta_W^{\nu N}$ as large as 0.002[13]; however more recent calculations[14,15] yield estimates of shifts at the 10^{-4} level. NuTeV has no ability to probe nucleon isospin violation directly. These effects would have to be inferred from a global analysis (CTEQ, MRST, GRV...) of deep inelastic scattering and other experiments that employ proton and deuterium targets.

2.4 Non-Standard Model Explanations

The new physics potential of precision neutrino scattering measurements has long been recognized[16]; however, it is challenging to find an effect that explains the NuTeV deviation without contradicting other precision measurements. Davidson *et al.* show that the following models *do not work*[7]: anything generating oblique type electroweak radiative corrections, models of anomalous neutrino couplings, extra Z' with generation-independent $SU(2)_L$ couplings, low energy minimal supersymmetry, and $SU(2)$ singlet or doublet leptoquarks. New physics models they identify that can explain a significant fraction of the NuTeV effect include contact interactions, possibly mediated by vector leptoquarks at a scale of ˜1.4 TeV, and a new $U(1)$ $B-3L_\mu$ gauge symmetry containing a Z' that de-couples from first generation leptons and mixes weakly with the standard model Z. The new Z' is compatible with existing data if it is either very heavy $\left(M_{Z'} \gtrsim 600 \text{ GeV}/c^2\right)$ or very light $\left(M_{Z'} \lesssim 10 \text{ GeV}/c^2\right)$.

Babu and Pati[17] claim that the NuTeV result is predicted by an extended supersymmetry model with an $SO(10)$ gauge symmetry. Their model predicts the value of $|V_{cb}|$ and the observed "neutrino counting deficit" at LEP Barshay and Kreyerhoff[18] invoke a new parity-conserving

neutrino interaction containing a very heavy new neutral lepton. In this model, the ν_μ effectively acquires an internal structure at distances $\lesssim 10^{-18}$ cm. Implications include a $\sin^2\theta_W^{\nu N}$ in accord with NuTeV, an accounting for the LEP neutrino deficit, and neutrinos that acquire strong interaction type cross sections for $E \gtrsim 10^{21}$ that could explain the presence of anomalous ultra-high-energy cosmic ray interactions Giunti and M. Laveder[19] attribute the NuTeV effect to the disappearance of electron-type neutrinos into sterile neutrinos with oscillation parameters $P(\nu_e \to \nu_s) = 0.21 \pm 0.07$ with $\Delta m^2 = 10 - 100$ eV^2. However, as noted by Davidson *et al.*, NuTeV's finding that direct measurement of the electron neutrino flux agrees with expectations likely already rules this scenario out. NuTeV has recently extended this work into an exclusion region for $\nu_\mu/\bar{\nu}_\mu \to \nu_e/\bar{\nu}_e$ oscillations[20]. Ma and Roy[21,22] considers two examples of new gauged $U(1)$ symmetries. The first adds a heavy triplet of new fermions to each family to provide an alternative see-saw mechanism for neutrino mass. The second gauges the symmetry $L_\mu - L_\tau$. Both models predict TeV scale Z' bosons that could explain the NuTeV anomaly if ZZ' mixing is kept small.

In summary, new physics models exist that can explain the NuTeV weak mixing angle result, but they are not simple extensions of the standard model.

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